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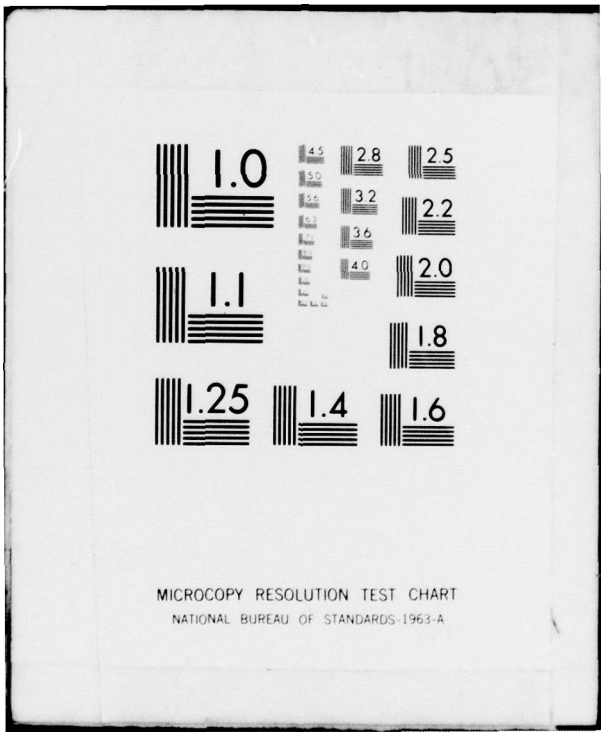
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Attenuation of Low Frequency Sound in the Sea: A Bibliography

David G. Browning
Robert H. Mellen
Special Projects Department

26 November 1979

NUSC
Naval Underwater Systems Center
Newport, Rhode Island • New London, Connecticut

Preface

This document was prepared under NUSC Project NO. A66210, Laboratory Independent Research Project ZR-000-01-01, "Space-Time Variability of Sound Propagation," Principal Investigator D. G. Browning, Sponsoring Activity NAVMAT 08T1, T. A. Kleback.

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This technical document contains a listing of all NUSC papers, presentations, and reports concerning the study of the attenuation of low frequency sound in the sea. A short historical narrative is included.

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INTRODUCTION

The attenuation of sound – the rate at which sound is dissipated during propagation – is one of the fundamental physical parameters of underwater acoustics. It is the relatively low value of attenuation of sound in sea water that makes acoustic systems superior to electromagnetic systems for submarine detection. Hence, attenuation is an essential factor in system design and performance prediction. As a result, attenuation has been the subject of continuing research programs to determine accurate values throughout the oceans of the world for all frequencies of interest.

In this document, the appropriate papers and presentations by members of the staff at the Naval Underwater Systems Center (NUSC) have been listed. These publications are grouped under the following headings:

1. Early work,
2. Thorp era,
3. Modeling results,
4. Scattering, glob theory,
5. Fresh water measurements,
6. Regional variation,
7. Internal waves,
8. pH dependence,
9. Laboratory measurements,
10. Practical formulas, sonar applications, and
11. Implications.

1.0 EARLY WORK

From the introduction of sonar in World War I through World War II and into the early 1950's, primary interest in attenuation was at frequencies above 10 kilocycles (now 10 kilohertz). The principal attenuation mechanism in sea water at these frequencies was found to be an absorption due to a $MgSO_4$ relaxation process that was proportional to the second power of the frequency.

During this era, NUSC (then the Underwater Sound Laboratory) conducted an extensive acoustic, meteorological, and oceanographic survey (AMOS) to extend results to lower frequencies (below 10,000 Hz). This produced what was called the Marsh-Schulkin formula based on the $MgSO_4$ absorption. However, some data from at-sea experiments indicated that measured values were greater than those predicted by this formula.

Although there was some controversy, specific experiments were sponsored to measure attenuation at low frequencies. The results suggested further that an anomaly existed. Pertinent papers, presentations, and reports are listed in this section.

1.1 PAPERS

1.1.1 M. Schulkin and H. W. Marsh "Sound Absorption in Sea Water," J. Acoust. Soc. Am., vol. 34, no. 6, 1962, pp. 864-865.

1.1.2 W. H. Thorp, "Deep-Ocean Sound Attenuation in the Sub- and Low-Kilocycle-per-Second Region," J. Acoust. Soc. Am., vol. 38, no. 4, 1965, pp. 648-654.

1.2 PRESENTATIONS

1.2.1 W. H. Thorp, "Some Recent Attenuation-Loss Measurements in the Sub- and Low-Kilocycle Region," 66th Meeting, Acoust. Soc. Am., Ann Arbor, MI, 6 to 9 November 1963 (J. Acoust. Soc. Am., vol. 6, no. 35, 1879(A), 1963).

1.2.2 B. Sussman, R. B. MacDonald, and W. G. Kanabis, "Attenuation-Loss Measurements in the Sofar Channel," 69th Meeting, Acoust. Soc. Am., Washington, DC, 2 to 5 June 1965 (J. Acoust. Soc. Am., vol. 37, no. 6, 1191(A), 1965).

1.2.3 W. H. Thorp, "Comparative Measurements of Low-Frequency Attenuation in the Deep Ocean Employing Sinusoidal and Explosive Sources," 74th Meeting, Acoust. Soc. Am., Miami Beach, FL, 14 November 1967, (J. Acoust. Soc. Am., vol. 42, no. 5, 1156(A), 1967).

1.3 REPORTS

1.3.1 H. W. Marsh and M. Schulkin, "Sound Transmission at Frequencies Between 2 and 25 Kilocycles per Second," NUSL Technical Memorandum No. 1110-110-54, Naval Underwater Systems Center, New London, CT, August 1954.

1.3.2 B. Sussman, R. B. MacDonald, and W. G. Kanabis, "Low Frequency Attenuation Studies," USL Technical Memorandum No. 911-16-64, Naval Underwater Systems Center, New London, CT, 13 October 1964.

1.3.3 M. C. Karamargin, "A Measurement of the Attenuation Coefficient at 4 kc and Source Level of the Fishbowl Projector," USL Technical Memorandum No. 906-08-65, Naval Underwater Systems Center, New London, CT, 12 October 1965.

1.3.4 W. H. Thorp, "Comparative Measurements of Low Frequency Attenuation in the Deep Ocean Employing Sinusoidal and Explosive Sources," NUSC Technical Memorandum No. 2211-149-67, Naval Underwater Systems Center, New London, CT, 28 November 1967.

2.0 THORP ERA

In 1965, W. H. Thorp, of NUSC, published a compendium of low-frequency attenuation data which showed conclusively that the measured results were greater than those predicted by the Marsh-Schulkin formula.

As a result, a measurement and analysis program was conducted at NUSC to determine the attenuation of sound in the sea at low frequencies. This effort had three principal goals:

1. To obtain a better analytical expression for the prediction of attenuation (this resulted in the Thorp formula).

2. To determine the variation of attenuation throughout the oceans (a series of experiments were conducted in extremes of temperature and salinity, such as the Red Sea and Hudson Bay).

3. To find the cause of this attenuation anomaly (all data were made readily available to interested members of the scientific community).

As with most fundamental research, the initial objectives were met but unexpected variations were uncovered. Pertinent papers, presentations, and reports are listed in this section.

2.1 PAPERS

2.1.1 W. H. Thorp, "Analytic Description of the Low-Frequency Attenuation Coefficient," J. Acoust. Soc. Am., vol. 42, no. 1, 1967, p. 270.

2.1.2 R. H. Mellen, W. H. Thorp, L. C. Maples, E. N. Jones, and D. G. Browning, "Very Low Frequency Attenuation Measurements," Proc. British Acoustical Society, Birmingham, England, 5 April 1971.

2.1.3 W. H. Thorp and D. G. Browning, "Attenuation of Low Frequency Sound in the Sea," J. of Sound and Vib., vol. 26, no. 4, 1973, pp. 571-575.

2.1.4 D. G. Browning, R. H. Mellen, and W. H. Thorp, "The Attenuation of Sound in the Sea," Proceedings, Satellite Symposium on Underwater Acoustics, Univ. of Birmingham, 1 August 1974, pp. (1.2) 1-7.

2.2 PRESENTATIONS

2.2.1 E. N. Jones, D. G. Browning, W. H. Thorp, and R. H. Mellen, "Temperature Dependence of Low Frequency Sound Attenuation in Fresh and Salt Water," 76th Meeting, Acoust. Soc. Am., Cleveland, OH, 20 November 1968 (J. Acoust. Soc. Am., vol. 45, no. 1, 306(A), 1969.

2.2.2 D. G. Browning, "Finite-Amplitude and Attenuation Research at NUSL," Ultrasonics Symposium, Michigan State University, 1 March 1968.

2.2.3 D. G. Browning and R. H. Mellen, "Attenuation and Finite Amplitude Effects in Underwater Sound," Narragansett Chapter, Acoust. Soc. Am., Providence, RI, 3 December 1968.

2.2.4 D. G. Browning, "Low Frequency Attenuation Research," Geophysics Seminar, Woods Hole Oceanographic Institution, Woods Hole, MA, 17 December 1968.

2.2.5 D. G. Browning, E. N. Jones, R. F. LaPlante, R. H. Mellen, and W. H. Thorp, "Project Massawa: Attenuation of Low-Frequency Sound in the Red Sea," 80th Meeting, Acoust. Soc. Am., Houston, TX, 3 to 6 November 1970 (J. Acoust. Soc. Am., vol. 49, no. 1, 107(A), 1971).

2.2.6 R. H. Mellen, W. H. Thorp, L. C. Maples, E. N. Jones, and D. G. Browning, "Very Low Frequency Sound Attenuation Measurements," Spring Meeting, British Acoustical Society, Birmingham, England, 5 April 1971.

2.2.7 W. H. Thorp, D. G. Browning, E. N. Jones, and R. H. Mellen, "Review of Low-Frequency Sound Attenuation in the Oceans," 81st Meeting, Acoust. Soc. Am., Washington, DC, 22 April 1971 (J. Acoust. Soc. Am., vol. 50, no. 1, 122(A), 1971).

2.2.8 D. G. Browning, E. N. Jones, R. H. Mellen, and W. H. Thorp, "Low-Frequency Sound Attenuation Anomaly in the Ocean: Recent Experimental Measurements," 81st Meeting, Acoust. Soc. Am., Washington, DC, 22 April 1971 (J. Acoust. Soc. Am., vol. 50, no. 1, 123(A), 1971).

2.2.9 D. G. Browning, E. N. Jones, R. H. Mellen, L. C. Maples, and W. H. Thorp, and J. M. Ross and C. Brochu (D.R.E.A.), "Sound Propagation and Reverberation Measurements in Hudson Bay," 81st Meeting, Acoust. Soc. Am., Washington, DC, 21 April 1971, (J. Acoust. Soc. Am., vol. 50, no. 1, 103(A), 1971).

2.2.10 D. G. Browning, R. H. Mellen, and W. H. Thorp, "The Attenuation of Sound in the Sea," Satellite Symposium on Underwater Acoustics, 8th International Congress of Acoustics, Birmingham, England, 1 August 1974.

2.3 REPORTS

2.3.1 D. G. Browning, "Acoustic Attenuation Research at NUSL," NUSL Technical Memorandum No. 2211-196-68, Naval Underwater Systems Center,

New London, CT, 19 July 1968.

2.3.2 E. N. Jones, D. G. Browning, R. H. Mellen, and W. H. Thorp, "The Effect of Temperature on Low-Frequency Sound Attenuation in Fresh and Salt Water," NUSL Technical Memorandum No. 2213-435-68, Naval Underwater Systems Center, New London, CT, 16 December 1968.

2.3.3 R. B. Lauer, The Attenuation of Underwater Sound, NUSC Technical Report NL-4025, Naval Underwater Systems Center, New London, CT, 2 November 1970.

2.3.4 D. G. Browning, W. H. Thorp, E. N. Jones, and R. H. Mellen, "Low Frequency Sound Attenuation Anomaly in the Ocean: Recent Experimental Measurements," NUSC Technical Memorandum No. TA11-147-71, Naval Underwater Systems Center, New London, CT, 8 June 1971.

2.3.5 W. H. Thorp, D. G. Browning, E. N. Jones, and R. H. Mellen, "A Review of Low Frequency Sound Attenuation in the Ocean," NUSC Technical Memorandum No. PL-178-71, Naval Underwater Systems Center, New London, CT, 18 June 1971.

2.3.6 E. N. Jones, D. G. Browning, W. H. Thorp, and R. H. Mellen, Sound Attenuation in the Red Sea, NUSC Technical Report 4101, Naval Underwater Systems Center, New London, CT, 2 August 1971.

2.3.7 D. G. Browning et al., Project CANUS: Sound Propagation and Reverberation Measurements in Hudson Bay, NUSC Technical Report 4221, Naval Underwater Systems Center, New London, CT, 1 December 1971.

2.3.8 D. G. Browning and W. H. Thorp, Attenuation of Low-Frequency Sound in the Ocean: NUSC Research Program 1967-1972, NUSC Technical Report 4581, Naval Underwater Systems Center, New London, CT, 4 January 1974.

3.0 MODELING RESULTS

The measurement of attenuation in the ocean is basically a sound propagation experiment; hence, assumptions have to be made concerning spreading loss, boundary interactions, and diffractive effects. The use of the deep-ocean sound channel simplified the consideration of some of these factors (surface scattering was eliminated, for example), but still some questions persisted.

With the advent of modeling programs for high-speed computers, we found ourselves in the forefront of studying sound-channel propagation predictions in order to understand attenuation experiments. Ironically, it appears that the results of the most sophisticated models tend to verify the simple assumptions that were made initially.

Pertinent papers, presentations, and reports are listed in this section.

3.1 PAPERS

3.1.1 D. G. Browning, "Environmental Factors Affecting Low Frequency Propagation in the Ocean," Proc. International Workshop on Low Frequency Propagation and Noise, (Published by Maury Center for Ocean Science), Vol. 2, 1977, pp. 769-799.

3.1.2 D. G. Browning, F. R. DiNapoli, R. H. Mellen, and H. G. Schneider, "Comments on Influence of Range-Dependent Environments on Low-Frequency Volume Attenuation Measurements in the Sea," J. Acoust. Soc. Am., vol. 62, no. 3, 1977, pp. 772-778.

3.1.3 H. G. Schneider, "Excess Sound Propagation Loss in a Stochastic Environment," J. Acoust. Soc. Am., vol. 62, no. 4, 1977, pp. 871-877.

3.1.4 R. H. Mellen and H. G. Schneider, "Diffusion Loss in Refractive Sound Channels: Bottom-Loss Effects," J. Acoust. Soc. Am., vol. 62, no. 4, 1977, pp. 1038-1040.

3.2 PRESENTATIONS

3.2.1 R. H. Mellen, D. G. Browning, F. R. DiNapoli, and P. G. Cable, "Limit of Spherical Spreading in the SOFAR Channel; Recent Experimental and Theoretical Determinations of Ro," 82nd Meeting, Acoust. Soc. Am., Denver, CO, 19 to 22 October 1971 (J. Acoust. Soc. Am., vol. 51, no. 1, 108(A), 1972).

3.2.2 F. R. DiNapoli and M. R. Powers, "Fast Field Program (FFP) and Attenuation Loss in Hudson Bay," 82nd Meeting, Acoust. Soc. Am., Denver, CO., 19 to 22 October 1971 (J. Acoust. Soc. Am., vol. 51, no. 1, 108(A), 1972).

3.2.3 D. G. Browning, M. R. Powers, R. H. Mellen, and F. R. DiNapoli, "Project Hiawatha Revisited: Application of FFP to Lake Superior Attenuation Experiment," 83rd Meeting, Acoust. Soc. Am., Buffalo, NY, 18 to 21 April 1972 (J. Acoust. Soc. Am., vol. 52, no. 1, 173(A), 1972).

3.2.4 F. R. DiNapoli, M. R. Powers, and D. G. Browning, "A Study of Very Low-Frequency Attenuation in the Deep Ocean Sound Channel," 84th Meeting, Acoust. Soc. Am., Miami Beach, FL, 1 December 1972 (J. Acoust. Soc. Am., vol. 53, no. 1, 299(A), 1973).

3.2.5 R. W. Bannister, R. N. Denham (DSE), D. G. Browning, and W. H. Thorp, "A Study of the Effect of Bottom Topology on Long Range Sound Propagation in the South Pacific," 85th Meeting, Acoust. Soc. Am., Boston, MA, 10 April 1973 (J. Acoust. Soc. Am., vol. 54, no. 1, 269(A), 1973).

3.2.6 R. W. Bannister, R. N. Denham (DSE), and D. G. Browning, "The Effect of Seamounts on Sound Channel Propagation," 86th Meeting, Acoust. Soc. Am., Los Angeles, CA, 30 October 1973 (J. Acoust. Soc. Am., vol. 55, no. 2, 417(A), 1974).

3.2.7 K. M. Guthrie, R. N. Denham, R. W. Bannister (DSE), and D. G. Browning, "Possible Effects of Velocity Profile Shape and Scattering Loss Distribution in SOFAR Propagation," 87th Meeting, Acoust. Soc. Am., New York, NY, 24 April 1974 (J. Acoust. Soc. Am., vol. 55, S43(A), Suppl. Spring 1974).

3.2.8 D. G. Browning, "Environmental Factors Affecting Low Frequency Propagation in the Ocean," International Workshop on Low Frequency Propagation and Noise, Woods Hole, MA, 14 to 19 October 1974.

3.2.9 D. G. Browning, R. H. Mellen, and F. R. DiNapoli, "Propagation in Sound Channels," Presentation TTCP Meeting, San Diego, CA, 29 October 1974.

3.2.10 D. G. Browning, "Environmental Factors and Low Frequency Propagation," NUSC Workshop on Wave Propagation in Underwater Acoustics, Mystic, CT, 19 November 1974.

3.2.11 M. R. Powers, D. G. Browning, and F. R. DiNapoli, "Analysis of Low-Frequency Sound Channel Propagation in Baffin Bay," 89th Meeting, Acoust. Soc. Am., Austin, TX, 7 to 11 April 1975 (J. Acoust. Soc. Am., vol. 57, S17(A), Suppl. No. 1, Spring 1975).

3.2.12 H. G. Schneider, "Excess Attenuation in a Stochastic Environment: Theory, Model, and Experiment," 92nd Meeting, Acoust. Soc. Am., San Diego, CA, 15 to 19 November 1976 (J. Acoust. Soc. Am., vol. 60, S35(A), Suppl. No. 1, Fall 1976).

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3.3.1 F. R. DiNapoli and M. R. Powers, The Fast Field Program (FFP) and Attenuation Loss in Hudson Bay, NUSC Technical Report 4253, Naval Underwater Systems Center, New London, CT, 19 April 1972.

3.3.2 D. G. Browning, M. R. Powers, R. H. Mellen, and F. R. DiNapoli, "Project Hiawatha Revisited: Application of FFP to Lake Superior Attenuation Experiment," NUSC Technical Memorandum No. PA4-133-72, Naval Underwater Systems Center, New London, CT, 19 May 1972.

3.3.3 F. R. DiNapoli, M. R. Powers, and D. G. Browning, "A Study of Very Low Frequency Attenuation in the Deep Ocean Sound Channel," NUSC Technical Memorandum No. PA4-307-72, Naval Underwater Systems Center, New London, CT, 13 December 1972.

3.3.4 M. R. Powers, D. G. Browning, and F. R. DiNapoli, "Analysis of Low-Frequency Sound Channel Propagation in Baffin Bay," NUSC Technical Memorandum No. TA11-27-76, Naval Underwater Systems Center, New London, CT, 5 February 1976.

4.0 SCATTERING, GLOB THEORY

As more attenuation experiments were conducted, it became apparent that at the lowest frequencies the measured attenuation was even higher than predicted by the Thorp formula. The additional component appeared to be frequency independent, in contrast to the absorption reactions.

Dr. R. H. Mellen, of NUSC, developed a simple formula based on the multiple scattering of sound, which provided a reasonable fit to the data. The scattering mechanism was due to changes in the physical properties of sea water, referred to as oceanographic inhomogeneities. Conceptually, the ocean can be thought of as composed of patches of water with different sound speeds. Sound would be scattered from these patches, or globs, as it travels through the ocean.

Pertinent papers, presentations, and reports are listed in this section.

4.1 PAPERS

4.1.1 R. H. Mellen, D. G. Browning, and J. M. Ross, "Attenuation of Randomly Inhomogeneous Sound Channels," J. Acoust. Soc. Am., vol. 56, no. 1, 1974, pp. 80-83.

4.1.2 R. H. Mellen, D. G. Browning, J. M. Ross, and H. M. Merklinger, "Low Frequency Attenuation in Baffin Bay," J. Acoust. Soc. Am., vol. 57, no. 5, 1975, pp. 1201-1202.

4.1.3 R. H. Mellen, "Sound Propagation in a Random Medium," Proc. International Workshop on Low Frequency Propagation and Noise, (published by Maury Center for Ocean Science) Vol. 1, 1977, pp. 387-411.

4.2 PRESENTATIONS

4.2.1 R. H. Mellen, D. G. Browning, and J. M. Ross, "Attenuation in Randomly Inhomogeneous Sound Channels," 86th Meeting, Acoust. Soc. Am., Los Angeles, CA, 31 October 1973.

4.2.2 R. W. Bannister, D. G. Browning, and R. N. Denham, "Effect of Deep-Ocean Turbulence on SOFAR Propagation," R.A.N.R.L. Propagation Symposium, Sydney, Australia, 28 November 1973.

4.2.3 H. Weinberg and R. H. Mellen, "Ray Diffusion in a Randomly Inhomogeneous Ocean," 87th Meeting, Acoust. Soc. Am., New York, NY, 23 to 26 April 1974 (J. Acoust. Soc. Am., vol. 55, no. S57(A), 1974).

4.2.4 R. H. Mellen, "Sound Propagation in a Randomly Inhomogeneous Ocean," Narragansett Chapter, Acoust. Soc. Am., Mystic, CT, 14 September 1974.

4.2.5 R. H. Mellen, "Sound Propagation in a Random Medium," Int. Workshop on Low Frequency Propagation and Noise, Woods Hole, MA, 14 to 19 October 1974.

4.2.6 D. G. Browning, R. H. Mellen, H. M. Merklinger, and J. M. Ross (D.R.E.A.), "Low Frequency Sound Attenuation in Baffin Bay," 88th Meeting, Acoust. Soc. Am., St. Louis, MO, 5 to 8 November 1974.

4.2.7 R. H. Mellen, "Attenuation of Sound in a Random Medium," NUSC Workshop on Wave Propagation in Underwater Acoustics, Mystic, CT, 19 November 1974.

4.2.8 R. H. Mellen and D. G. Browning, "Some Acoustic Effects of Internal Microstructure," SACLANT Ocean Acoustics Modeling Conference, LaSpezia, Italy, 8 to 11 September 1975.

4.2.9 R. H. Mellen, D. G. Browning, and L. Goodman, "Ray Diffusion in Inhomogeneous Sound Channels," 91st Meeting, Acoust. Soc. Am., Washington, DC, 5 to 9 April 1976.

4.3 REPORTS

4.3.1 R. H. Mellen, "Attenuation in Randomly Inhomogeneous Sound Channels," NUSC Technical Memorandum No. PA4-133-73, Naval Underwater Systems Center, New London, CT, 30 May 1973.

4.3.2 R. H. Mellen, "Attenuation in Randomly Inhomogeneous Sound Channels," SACLANTCEN Memorandum SM-16, SACLANT Center, LaSpezia, Italy, 15 August 1973.

4.3.3 R. H. Mellen, "Ray Diffusion in an Ocean-Front Region," SACLANTCEN Memorandum SM-22, SACLANT Center, LaSpezia, Italy, 15 September 1973.

4.3.4 R. H. Mellen, "Sound Propagation in a Randomly Inhomogeneous Ocean," NUSC Technical Memorandum No. PA4-273-73, Naval Underwater Systems Center, New London, CT, 2 November 1973.

5.0 FRESH-WATER MEASUREMENTS

There were many explanations put forth for the low-frequency attenuation anomaly in sea water. The most likely hypothesis, based on a fit to the data, was a chemical relaxation reaction similar to the $MgSO_4$ absorption observed at high frequencies.

An indirect way to verify this hypothesis was to make comparative fresh-water measurements (the chemical relaxation mechanism would not be present). Only three lakes in the world had conditions favorable for a low-frequency attenuation measurement:

1. Lake Superior (U.S.A./Canada),
2. Lake Tanganyika (Africa), and
3. Lake Baikal (Russia).

Results were obtained from the first two lakes. Despite a spirited political campaign, it has not been possible to arrange an experiment in the third lake as yet. It was not until further laboratory measurements were made that the data could be fully explained.

Pertinent papers, presentations, and reports are listed in this section.

5.1 PAPERS

5.1.1 D. G. Browning, W. H. Thorp, and R. H. Mellen, "Attenuation of Low-Frequency Sound in Fresh Water," Proc. 6th International Congress on Acoustics, Tokyo, Japan, 22 August 1968, pp. L-9,12.

5.1.2 D. G. Browning, E. N. Jones, R. H. Mellen, and W. H. Thorp, "Attenuation of Low-Frequency Sound in Freshwater," Science, vol. 162, 6 December 1968, pp. 1120-1121.

5.1.3 D. G. Browning et al., "Lake Tanganyika Sound Attenuation Experiment," Nature – Physical Science, vol. 240, no. 100, 27 November 1972, pp. 86-88.

5.1.4 R. H. Mellen, D. G. Browning, and V. P. Simmons, "Acoustic Attenuation in Lake Tanganyika," Nature, vol. 277, no. 5695, 1 February 1979, pp. 374-375.

5.2 PRESENTATIONS

5.2.1 D. G. Browning, W. H. Thorp, F. C. Friedel, and R. F. LaPlante, "Project HIAWATHA: Long-Range Shallow-Water Sound Propagation in Lake Superior," 75th Meeting, Acoust. Soc. Am., Ottawa, Canada, 23 May 1968 (J. Acoust. Soc. Am., vol. 44, no. 1, 381(A), 1968).

5.2.2 D. G. Browning, W. H. Thorp, and R. H. Mellen, "Project Hiawatha: Underwater Acoustics Research in the Great Lakes," 12th Conference on Great Lakes Research, Ann Arbor, MI, 5 May 1969.

5.2.3 D. G. Browning et al., "Project Bold Venture: Lake Tanganyika Sound Attenuation Experiment," 82nd Meeting, Acoust. Soc. Am., Denver, CO, 19 to 22 October 1971 (J. Acoust. Soc. Am., vol. 51, no. 1, 108(A), 1972).

5.2.4 D. G. Browning, E. N. Jones, R. H. Mellen, and W. H. Thorp, "Slow Relaxation Processes in Water," ONR Symposium on Water Structure, Washington, DC, March 1969.

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5.3.1 D. G. Browning, "Investigation of the Low Frequency Attenuation Anomaly in Sea Water: A Proposal for Measurements in Lake Superior," NUSL Technical Memorandum No. 2111-29-67, Naval Underwater Systems Center, New London, CT, 16 February 1967.

5.3.2 D. G. Browning, E. N. Jones, R. H. Mellen, and W. H. Thorp, "Attenuation Research: A Case for Lake Tanganyika," NUSL Technical Memorandum No. 2111-133-68, Naval Underwater Systems Center, New London, CT, 2 May 1968.

5.3.3 D. G. Browning, W. H. Thorp, F. C. Friedel, and R. F. LaPlante, "Project Hiawatha: Long-Range Shallow-Water Sound Propagation in Lake Superior," NUSL Technical Memorandum No. 2211-173-68, Naval Underwater Systems Center, New London, CT, 20 June 1968.

5.3.4 D. G. Browning, J. M. Gorman, E. N. Jones, W. H. Thorp, R. H. Mellen, and F. G. Weigle, "Project Bold Venture – Lake Tanganyika Sound Attenuation Experiment," NUSC Technical Memorandum No. TA131-59-72, Naval Underwater Systems Center, New London, CT, 14 February 1972.

5.3.5 E. N. Jones, J. M. Gorman, W. H. Thorp, and D. G. Browning, Hydrology and Acoustic Measurements of Lake Tanganyika, NUSC Technical Report 4577, Naval Underwater Systems Center, New London, CT, 10 September 1973.

5.3.6 D. G. Browning and F. C. Friedel, "Project Hiawatha Revisited (Again): Additional Low Frequency Data from Lake Superior," NUSC Technical Memorandum No. 781082, Naval Underwater Systems Center, New London, CT, 28 April 1978.

6.0 REGIONAL VARIATION

Although the Thorp formula and a simple scattering model gave improved predictions of attenuation, the accumulation of data from throughout the world's oceans showed that significant regional differences occurred. Perhaps most striking was that the anomalous attenuation in the Pacific Ocean was only one-half that measured in the Atlantic Ocean.

Pertinent papers, presentations, and reports are listed in this section.

6.1 PAPERS

6.1.1 R. W. Bannister, R. N. Denham, K. M. Guthrie (DSE), and D. G. Browning, "SOFAR Propagation in the Oceans of the Southern Hemisphere," Proc. 8th International Congress on Acoustics, London, England, 1974, p. 439.

6.1.2 R. H. Mellen,and D. G. Browning, "Low Frequency Sound Attenuation in the Pacific Ocean," J. Acoust. Soc. Am., vol. 59, no. 3, 1976, pp. 700-702.

6.1.3 R. W. Bannister, R. N. Denham, K. M. Guthrie, and D. G. Browning, "Project Tasman Two: Low Frequency Propagation Measurements in the South Tasman Sea," J. Acoust. Soc. Am., vol. 62, no. 4, 1977, pp. 847-859.

6.2 PRESENTATIONS

6.2.1 D. G. Browning et al., "Project Kiwi One: Very Low Frequency Acoustic Propagation Measurements in the South Pacific Ocean," 84th Meeting, Acoust. Soc. Am., Miami Beach, FL, 1 December 1972, (J. Acoust. Soc. Am., vol. 53, no. 1, 299(A), 1973).

6.2.2 D. G. Browning, E. N. Jones, and W. H. Thorp, "Low Frequency Sound Attenuation in the Indian Ocean," 84th Meeting, Acoust. Soc. Am., Miami Beach, FL, 1 December 1972 (J. Acoust. Soc. Am., vol. 53, no. 1, 299(A), 1973.

6.2.3 D. G. Browning, "Attenuation of Sound in the Sea: Recent Measurement," Defense Scientific Establishment Seminar, Auckland, N.Z., 27 July 1973.

6.2.4 D. G. Browning, "Current State of Low Frequency Sound Measurements," New Zealand Defense Research Board, Auckland, N.Z., 13 August 1973.

6.2.5 R. W. Bannister, R. N. Denham, D. G. Browning (DSE), K. M. Guthrie, and A. C. Kibblewhite (University of Auckland), "SOFAR Propagation in the South Pacific Ocean," 86th Meeting, Acoust. Soc. Am., Los Angeles, CA, 31 October 1973 (J. Acoust. Soc. Am., vol. 55, no. 2, 417(A), 1974).

6.2.6 D. G. Browning, R. N. Denham, and R. W. Bannister, "Attenuation of Sound in Seawater at SONAR Frequencies," R. Australian Navy Res. Lab. Propagation Symposium, Sydney, Australia, 28 November 1973.

6.2.7 R. W. Bannister, R. N. Denham, K. M. Guthrie (DSE), and D. G. Browning, "SOFAR Propagation in the Oceans of the Southern Hemisphere," 8th International Congress on Acoustics, London, England, 26 July 1974.

6.2.8 R. W. Bannister, R. N. Denham, K. M. Guthrie (DSE), and D. G. Browning, "Oceanographic Parameters, Bathymetric Features, and Their Effect on Sound Propagation in the South Pacific Ocean," 10th New Zealand National Electronics Conv., Auckland, N.Z., 29 August 1974.

6.2.9 R. H. Mellen and D. G. Browning, "Low Frequency Attenuation in the Pacific Ocean," 89th Meeting, Acoust. Soc. Am., Austin, TX, 11 April 1975 (J. Acoust. Soc. Am., vol. 57, S65(A), Suppl. No. 1, Spring 1975).

6.2.10 R. W. Bannister, R. N. Denham, K. M. Guthrie (DSE), and D. G. Browning, "Project Tasman Two: Low Frequency Propagation Measurements in the South Tasman Sea," 90th Meeting, Acoust. Soc. Am., Washington, DC, 5 to 9 April 1976 (J. Acoust. Soc. Am., vol. 59, S85(A), Suppl. No. 1, Spring 1976).

6.3 REPORTS

6.3.1 E. N. Jones and W. H. Thorp, "Operation Ghubbet: Outline of Experimental Phase," NUSC Technical Memorandum No. TA13-242-71, Naval Underwater Systems Center, New London, CT, 19 November 1971.

6.3.2 W. H. Thorp and W. R. Schumacher, "Project Kiwi One Cruise Report," NUSC Technical Document No. 4455, Naval Underwater Systems Center, New London, CT, 12 February 1973.

6.3.3 D. G. Browning, E. N. Jones, and W. H. Thorp, Low Frequency Sound Attenuation in the Gulf of Aden, NUSC Technical Report 4501, Naval Underwater Systems Center, New London, CT, 5 March 1973.

6.3.4 R. W. Bannister, "Kiwi One: Louisville Ridge Cruise," Defense Scientific Establishment Technical Note 73/6, New Zealand Defense Scientific Establishment, Auckland, N.Z., 1 May 1973.

6.3.5 D. G. Browning, W. R. Schumacher, R. W. Bannister, and R. N. Denham (DSE), Project Kiwi One: Low Frequency Sound Attenuation Measurements in the South Pacific Ocean, NUSC Technical Report 4949, Naval Underwater Systems Center, New London, CT, 1 July 1975.

6.3.6 D. G. Browning, P. D. Koenigs, and R. F. LaPlante, "Attenuation Coefficients for the Caribbean Sea and the Gulf of Mexico," NUSC Technical Memorandum No. TA11-200-75, Naval Underwater Systems Center, New London, CT, 10 July 1975.

6.3.7 D. G. Browning, "The Attenuation of Sound in the Sea," 'Know Your Center Series,' NUSCOPE, 19 March 1976.

7.0 INTERNAL WAVES

Another possible explanation for the scattering component of low frequency attenuation is the interaction with internal waves. The theory of internal waves in the ocean is being developed by Professor W. Munk and his associates at Scripps.

Professor A. C. Kibblewhite (Univ. of Auckland, N. Z.) has shown that the scattering component can have a regional variation.

Comparing the relative merits of the glob theory and internal waves, Mellen and Browning found that attenuation data from surface ducts indirectly would support the internal wave explanation.

Recent work by M. Fecher et al. confirms that regional variation in the scattering component can be explained by internal wave activity.

Pertinent papers and presentations are listed in this section.

7.1 PAPERS

7.1.1 R. H. Mellen, D. G. Browning, and L. Goodman, "Diffusion Loss in a Stratified Sound Channel," J. Acoust. Soc. Am., vol. 60, no. 5, 1976, pp. 1053-1055.

7.1.2 R. H. Mellen and D. G. Browning, "Attenuation in Surface Ducts," J. Acoust. Soc. Am., vol. 63, no. 5, 1978, pp. 1624-1626.

7.1.3 D. G. Browning, R. H. Mellen, and L. C. Maples, "The Ocean as an Inhomogeneous Medium," Proc. FASE 78 (European Congress of Acoustics), Warsaw, Poland, September 1978.

7.2 PRESENTATIONS

7.2.1 D. G. Browning, "Acoustics and Ocean Variability," Presentation to Scientific Committee of National Representatives (SACLANT), New London, CT, 26 May 1977.

7.2.2 M. J. Fecher, D. G. Browning, and R. H. Mellen, "Regional Dependence of Very Low Frequency Sound Attenuation in the Deep Sound Channel: Correlation with Internal Wave Measurements," 96th Meeting, Acoust. Soc. Am., Honolulu, HI, December 1978 (J. Acoust. Soc. Am., vol. 64, S46(A), Suppl. No. 1, Fall 1978).

7.2.3 R. H. Mellen, "Sound Propagation in an Inhomogeneous Ocean," Int. Congress on Cavitation and Inhomogeneities in Underwater Acoustics, Gottingen, F.G.R., 9 to 11 July 1979.

8.0 pH DEPENDENCE

A breakthrough that explained all the variation in chemical absorption observed in the ocean was obtained. Drs. Simmons and Fisher, at Scripps, had shown that boron was the key element in the newly-discovered relaxation process. During Simmons' thesis defense, it was suggested that this reaction might be pH dependent. Mellen and Browning followed up on this suggestion and found that all existing data could be related to local values of pH.

Pertinent papers and presentations are listed in this section.

8.1 PAPERS

8.1.1 R. H. Mellen and D. G. Browning, "Variability of Low Frequency Sound Absorption in the Ocean: pH Dependence," J. Acoust. Soc. Am., vol. 61, no. 3, 1977, pp. 704-706.

8.1.2 D. G. Browning and R. H. Mellen, "The Attenuation of Sound in the Sea," Proc. 9th International Congress on Acoustics, Madrid, Spain, 1977, p. 657.

8.1.3 R. H. Mellen and D. G. Browning, "The Effect of pH on Low Frequency Absorption in the Ocean," Proc. Meeting on Sound Propagation and Underwater Systems, Imperial College, London, England, 1 April 1978.

8.2 PRESENTATIONS

8.2.1 R. H. Mellen and D. G. Browning, "Variability of Low Frequency Sound Absorption in the Ocean: pH Dependence," 92nd Meeting, Acoust. Soc. Am., San Diego, CA, 15 to 19 November 1976 (J. Acoust. Soc. Am., vol. 60, S36(A), Suppl. No. 1, Fall 1976).

8.2.2 R. H. Mellen and D. G. Browning, "The Effect of pH on Low Frequency Sound Absorption in the Ocean," Meeting on Sound Propagation and Underwater Systems, Imperial College, London, England, 10 April 1978.

8.2.3 F. C. Friedel, R. L. Martin, and D. G. Browning, "Low Frequency Sound Attenuation in the Labrador Sea-Baffin Bay Region," 95th Meeting, Acoust. Soc. Am., Providence, RI, 18 May 1978 (J. Acoust. Soc. Am., vol. 63, Suppl. No. 1, Spring 1978).

9.0 LABORATORY MEASUREMENTS

Fisher and Simmon's identification of the boron relaxation reaction through laboratory measurements renewed interest in this technique. Mellen, establishing this work at NUSC, discovered a third reaction and is conducting an extensive study of the pH and temperature dependence of the significant reactions in sea water.

Pertinent papers and presentations are listed in this section.

9.1 PAPERS

9.1.1 R. H. Mellen, D. G. Browning, and V. P. Simmons, "Sound Absorption in the Sea: A Third Chemical Relaxation," J. Acoust. Soc. Am., vol. 65, no. 4, 1979, pp. 923-925.

9.1.2 R. H. Mellen, D. G. Browning, and V. P. Simmons, "Acoustic Absorption by a Magnesium Carbonate Ion-Pair Relaxation," Nature, vol. 279, no. 5715, pp. 705-706, June 21, 1979.

9.2 PRESENTATIONS

9.2.1 D. G. Browning, "Attenuation of Sound in the Sea," Physics Colloquim, Naval Postgraduate School, Monterey, CA, 27 April 1979.

10.0 PRACTICAL FORMULAE, SONAR APPLICATIONS

The end result of this work is to provide the best possible practical formula for the prediction of attenuation at any location in the ocean and for all frequencies.

Whenever a result was obtained that was a significant improvement over existing formulae, it was presented, rather than delay until a 'wrap-up' formula was found.

It now appears that we have a formula to meet the requirements of anti-submarine warfare (ASW); the objective has been met.

Pertinent papers, presentations, and reports are listed in this section.

10.1 PAPERS

10.1.1 D. G. Browning and R. H. Mellen, "Environmental Factors Affecting Sonar Performance," Proc. EASCON '75, Washington, DC, September 1975, pp. 69A-69D.

10.2 PRESENTATIONS

10.2.1 R. W. Bannister, R. N. Denham, and D. G. Browning, "Attenuation of Sound in Seawater at SONAR Frequencies," R.A.N.R.L. Propagation Symposium, Sydney, Australia, 28 November 1973.

10.2.2 D. G. Browning and R. H. Mellen, "Environmental Factors Affecting Sonar Performance," Proc. EASCON '75, Washington, DC, September 1975.

10.2.3 R. B. Lauer, G. Botseas, D. G. Browning, and F. R. DiNapoli, "A Study of the Effect of Propagation Loss Variability on Sonar Performance Prediction," 91st Meeting, Acoust. Soc. Am., Washington, DC, 5 to 9 April 1976 (J. Acoust. Soc. Am., vol. 59, S42(A), Suppl. No. 1, Spring 1976).

10.2.4 D. G. Browning, "Recent Measurements in Acoustics," Pres. Submarine Officers' Advanced Course (Class 7604), New London, CT, 5 August 1976.

10.2.5 D. G. Browning and W. A. von Winkle, "Fluctuations in Acoustic Parameters and Their Effects on Sonar System Design," IEEE International Conference on Acoustics, Speech, and Signal Processing, Hartford, CT, 9 to 11 May 1977.

10.2.6 D. G. Browning, "Acoustics and Ocean Variability," Pres. Scientific Committee of National Representatives (SACLANT), New London, CT, 26 May 1977.

10.2.7 D. G. Browning, V. P. Simmons, and R. J. Urick (TRACOR), "Practical Values of Low Frequency Attenuation in the Sea," 96th Meeting,

Acoust. Soc. Am., Honolulu, HI, 1 December 1978 (J. Acoust. Soc. Am., vol. 64, S75(A), Suppl. No. 1, Fall 1978).

10.3 REPORTS

10.3.1 D. G. Browning and W. A. Von Winkle, "Fluctuations in Acoustic Parameters and Their Effects on Sonar System Design," NUSC Technical Memorandum No. 771103, Naval Underwater Systems Center, New London, CT, 2 June 1977.

10.3.2 D. G. Browning, "Attenuation of Sound in the Sea," NUSC Technical News Letter, vol. 3, no. 9, Naval Underwater Systems Center, New London, CT, September 1978.

11.0 IMPLICATIONS

As the mechanisms that cause the attenuation of sound are understood, measured changes in attenuation can be attributed to corresponding chemical and physical changes in the ocean. This implies that acoustic waves can be used to identify water masses and regions of turbulence, and even to estimate the life-support capability of an ocean area. In addition, acoustic data now provide the best available information on the chemical kinetics in sea water.

Pertinent papers and presentations are listed in this section.

11.1 PAPERS

11.1.1 D. G. Browning and R. W. Bannister (DSE), "Project Kiwi One: New Dimensions in Underwater Sound," U. S. Naval Institute Proceedings, vol. 102, no. 1/875, January 1976, pp. 104-105.

11.1.2 A. C. Kibblewhite (Univ. of Auckland) and D. G. Browning, "The Identification of Major Oceanographic Fronts by Long Range Acoustic Propagation Measurements," Deep Sea Research, vol. 25, no. 11, November 1978, pp. 1107-1118.

11.2 PRESENTATIONS

11.2.1 D. G. Browning, R. N. Denham, R. W. Bannister, and K. M. Guthrie (DSE), "Using Sound to Understand Oceans," EASCON '77, Alexandria, VA, 27 September 1977.

11.2.2 D. G. Browning, "Investigations of Major Oceanographic Fronts Using Underwater Sound," Physics Seminar, Univ. of Rhode Island, Kingston, RI, 7 April 1978.

11.2.3 D. G. Browning, "Low Frequency Sound Attenuation Mechanisms in the Sea: Oceanographic Applications," The Americal Physical Society - New England Section, Wesleyan University, Middletown, CT, 14 April 1978.

11.2.4 D. G. Browning and A. C. Kibblewhite (Univ. of Auckland), "Oceanographic Mapping by Use of Low Frequency Acoustic Attenuation Measurements," 96th Meeting, Acoust. Soc. Am., Honolulu, HI, December 1978 (J. Acoust. Soc. Am., vol. 64, S75A, Suppl. No. 1, Fall 1978).

11.2.5 D. G. Browning and R. H. Mellen, "Attenuation of Sound Throughout the Oceans of the World," 49th Congress, Australian and New Zealand Assoc. for the Advancement of Science, Auckland, New Zealand, 22 to 26 January 1979.

11.2.6 D. G. Browning, "Oceanography and Acoustics of the Oceans in the Southern Hemisphere," Oceanography Seminar, Naval Postgraduate School, Monterey, CA, 8 May 1979.

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